

Virtual Seismometers in Geothermal Systems: Looking Inside the Microseismic Cloud

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ABSTRACT

Thousands of microquakes are often associated with an injection at geothermal sites. When processed using novel geophysical techniques, this cloud of microquakes effectively illuminates the subsurface, and can be used to monitor plume growth, measure source properties and identify otherwise hidden structures. The virtual seismometer method (VSM) is a new technique of seismic interferometry that provides precise estimates of the Green function (GF) between earthquakes. It is very sensitive to the source parameters (location, mechanism and magnitude) and to the Earth structure in the source region.

Using VSM, we are able to focus sharply on the cloud of microseismicity. We can monitor the evolution of seismicity over time, measure changes in the style of faulting and sort microseisms by location and magnitude. Our ultimate intent is to use it to image structures within the microseismic cloud in an attempt to identify previously un-observed fault zones. In simple terms VSM involves correlating the waveforms from a pair of events recorded at an individual station and then stacking the results over all stations to obtain the final result. In the far-field, when most of the stations in a network fall along a line between the two events, the result is an estimate of the GF between the two, modified by the source terms. In this geometry each earthquake is effectively a virtual seismometer recording all the others. When applied to microquakes, this alignment is often not met, and we need to address the effects of the geometry between the two microquakes relative to each seismometer. Nonetheless, the technique is quite robust, and highly sensitive to the microseismic cloud.

Using data from the Salton Sea geothermal region, we demonstrate the power of the technique, illustrating our ability to scale from the far-field, where sources are well separated, to the near field where their locations fall within each other's uncertainty ellipse. We are able to separate closely spaced events into separate subclusters and to measure differences in faulting mechanism.

1. INTRODUCTION

In seismology, the Green's function (GF) is defined as the response of the Earth at one point due to an impulsive source at another. In simple terms, GFs are the data recorded by seismometers once the peculiarities of the source and instrument are removed. Because of reciprocity, the seismic record would be the same even if the locations of the impulsive source and the seismometer were switched. In recent years, seismologists have used this principle in the emerging field of seismic interferometry to treat seismometers as virtual earthquakes and earthquakes as virtual seismometers.

In 2003, Campillo and Paul used the cross correlation of the scattered energy that arrives after an earthquake (called the coda) recorded at different seismic stations to obtain the GF of the Earth between the stations (Campillo and Paul, 2003). Since then, the field of seismic interferometry has rapidly expanded and produced highly detailed images of the crust and upper mantle. To date, seismic interferometry has focused on using the ambient noise field to obtain image the interior of the Earth between pairs of stations. However, it is straightforward to flip the geometry used by Campillo and Paul and focus instead on the structure between pairs of earthquakes. Hong and Menke (2006) took advantage of this theory to study wear along the San Jacinto fault. The theory was developed more completely by Curtis et al. (2009), who demonstrated that you can convert earthquakes into "virtual seismometers" by using the correlation properties of records from distant arrays.

Our method, similar to that of Curtis et al., involves correlating the coda of pairs of earthquakes recorded at individual seismic stations and then stacking the results over all stations to obtain the final GF. By effectively replacing each earthquake with a "virtual seismometer" recording all the others, the technique isolates the portion of the data that is sensitive to the source region and dramatically increases our ability to see into tectonically active features where seismic stations either can't or haven't been located, such as at depth in fault zones.

In many ways, VSM is the converse of ambient noise correlation (ANC), also known as the "virtual earthquake" technique. Each technique has its strengths relative to the other. VSM is very fast, only a few minutes of data are needed, compared to the weeks to years of continuous data often required for ANC. Furthermore, the GF obtained by VSM has the same frequency content as the earthquakes, while the spectrum of ANC is determined by the natural background noise. For microseismic studies, this allows us to obtain very high frequency estimates of the GF between microquakes. Both techniques gain power rapidly as more elements are added to the system according to the equation $N*(N-1)/2$. For ANC, these elements are the individual seismometers, for VSM the elements are the individual earthquakes. The key strength of ANC is that timing and location of the elements are perfectly known and the GF is equivalent to that of a simple impulsive source. For VSM, neither the timing nor the location of the elements is known and the correlation waveform is the GF, modified by both moment tensors. For this reason, ANC is quite sensitive to the heterogeneities in the

Earth structure, while VSM is most sensitive to the source parameters, which need to be accounted for before Earth structure can be recovered.

2. MICROQUAKES AS VIRTUAL SEISMOMETERS

In the far-field, when most of the stations in a network fall along a line between two earthquakes, the result of the correlation is an estimate of the GF between the two, modified by the source terms. In this geometry each earthquake is effectively a virtual seismometer recording all the others. We applied VSM to well defined shots from the Salton Sea Imaging Project (SSIP), to define the sensitivity and precision of the technique (figure 1). Even when two earthquakes line up at an angle to the recording network, the effects of the geometry can be removed before stacking to obtain the GF estimate. However, in microseismic systems, the uncertainty in location and origin time are compounded by the fact that the distance between individual stations in the recording network may be much farther from one another than they are from the zone of microseismicity and the effects of geometry become more pronounced.

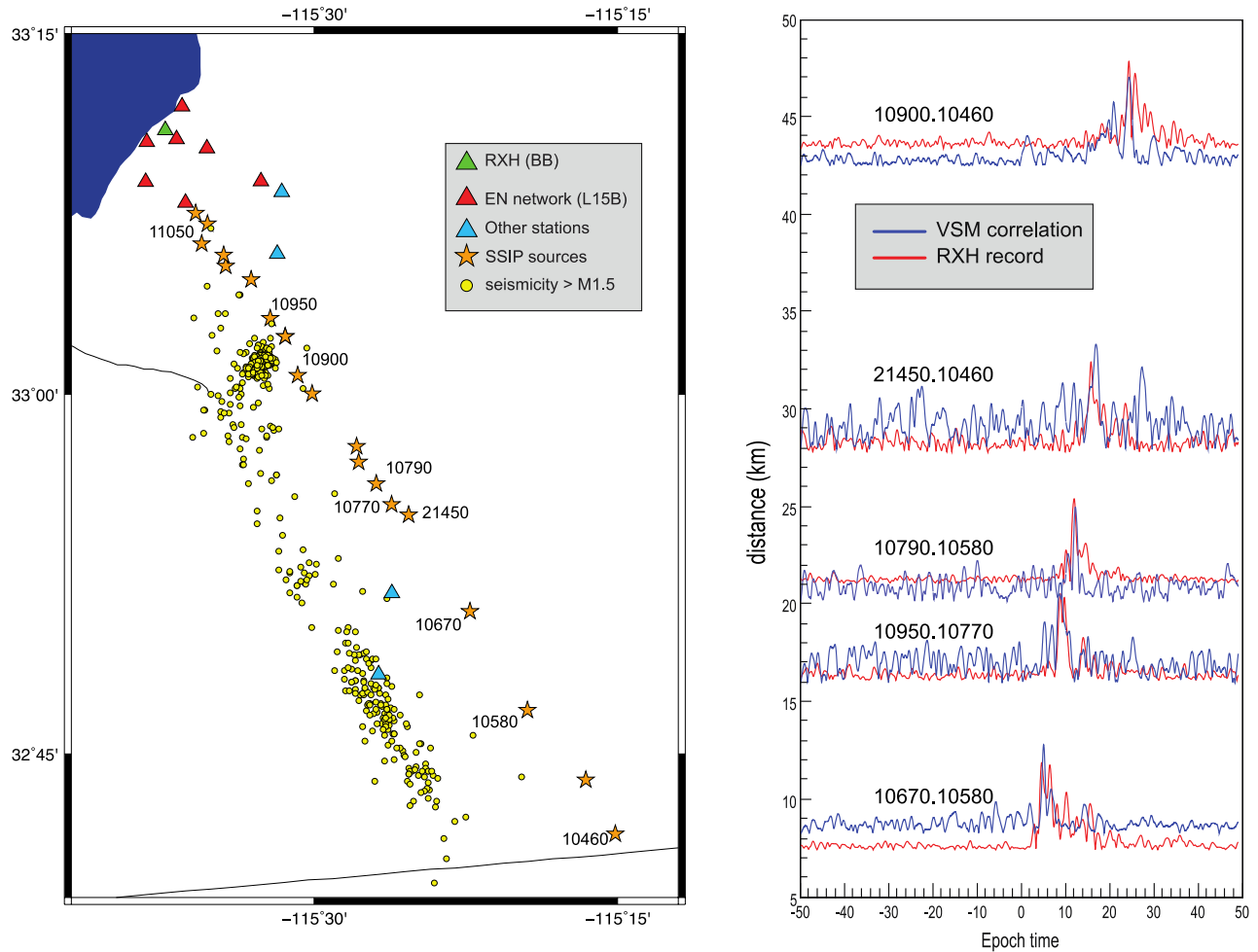


Figure 1: (Left) a map of seismicity and station coverage south of the Salton Sea. (Right) SSIP shot data recorded at broadband station RXH (red) are compared to virtual seismograms created using the correlation of the SSIP sources (blue).

When VSM is applied to microseismic data we are typically working in the very near field, where the distance between microquakes can be larger than the distance from an individual microquake to elements of the recording network. At this range, microquakes often fall within each other's uncertainty ellipse. We apply Bayesian techniques to increase the precision of the relative locations and Matched Field Processing to identify subclusters within the population. An example of the technique for the deployment at the Newberry geothermal field is shown in figure 2. The spectrum of the calculated signal is defined by the recorded seismicity and we can obtain very high frequency estimates of the Green functions using this technique.

Adjoint techniques (Tromp, Tape and Liu, 2005) allow us to calculate the sensitivity of the model parameters to the observables and show that kernels for virtual seismometers are comparable to those for actual seismometers and for many geometries, even a simple stack of the correlation waveforms result in a match for the correct GF. By isolating the portion of the wavefield sensitive to the tectonically active zone, VSM collapses the computational scale of the problem, often by several orders of magnitude. This enables fast inversion of the microseismic source focal mechanisms, as well as waveform propagation and Earth structure in the active zone.

Example of a microquake as a virtual seismometer

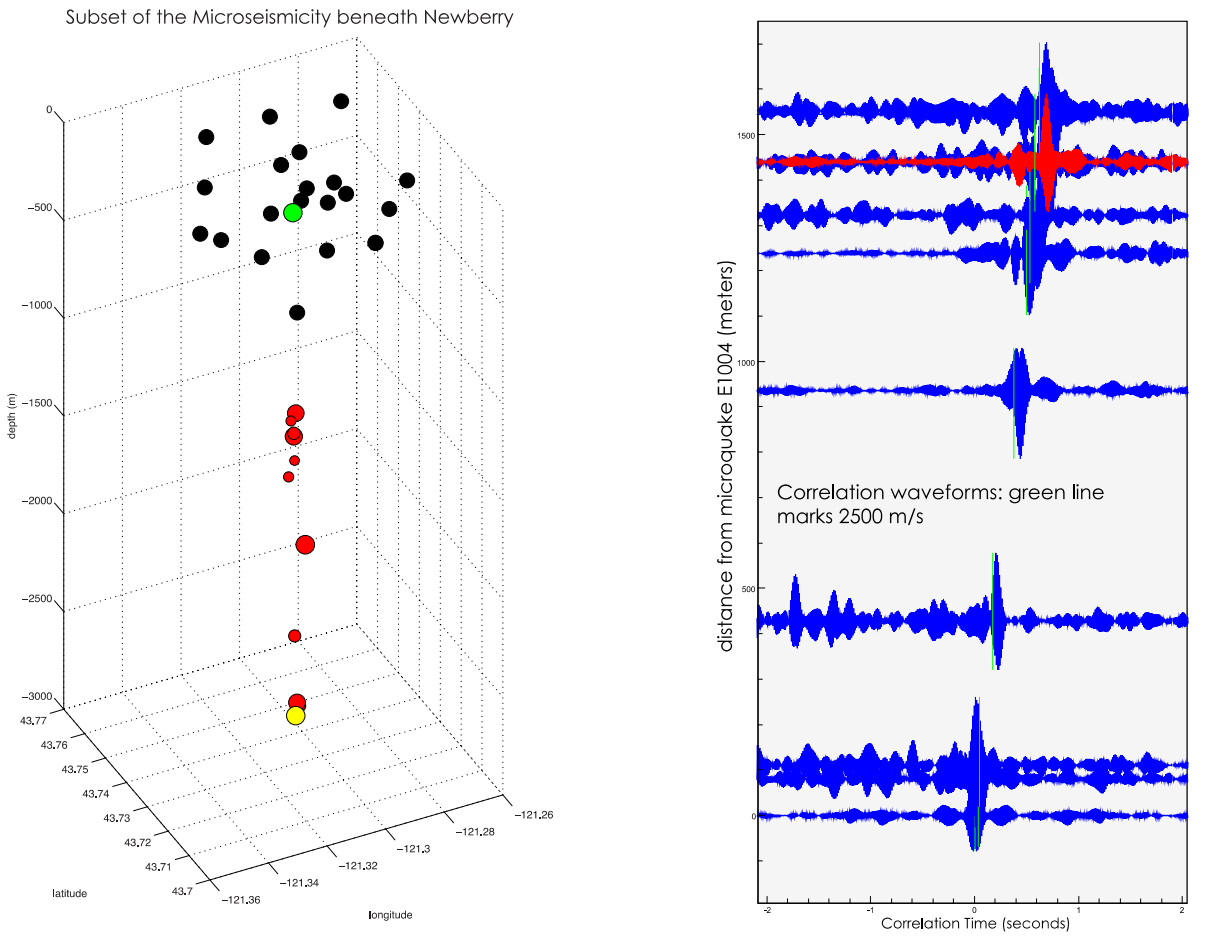


Figure 2: (Left) A view of the network at Newberry (black) and a subset of the microseismicity beneath it (red). The yellow circle denotes a microquake which is being treated as the virtual seismometer recording the others. The central element of the network (green) was used in the VSM calculations shown at right. **(Right)** A profile of the virtual seismograms calculated.

3. CONCLUSIONS

Microseismicity is closely associated with geothermal development and can be used to monitor the evolution of the pressure field due to fluid injection. VSM is a technique that allows us to focus directly on this zone of microseismicity, illuminating the subsurface precisely where the pressures are changing. This has the potential to image the evolution of seismicity over time, including changes in the style of faulting as injection proceeds. Given sufficient microseismicity we can begin to calculate detailed evolution of the wavefield.

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